N87-25277

TURBULENCE MODELS

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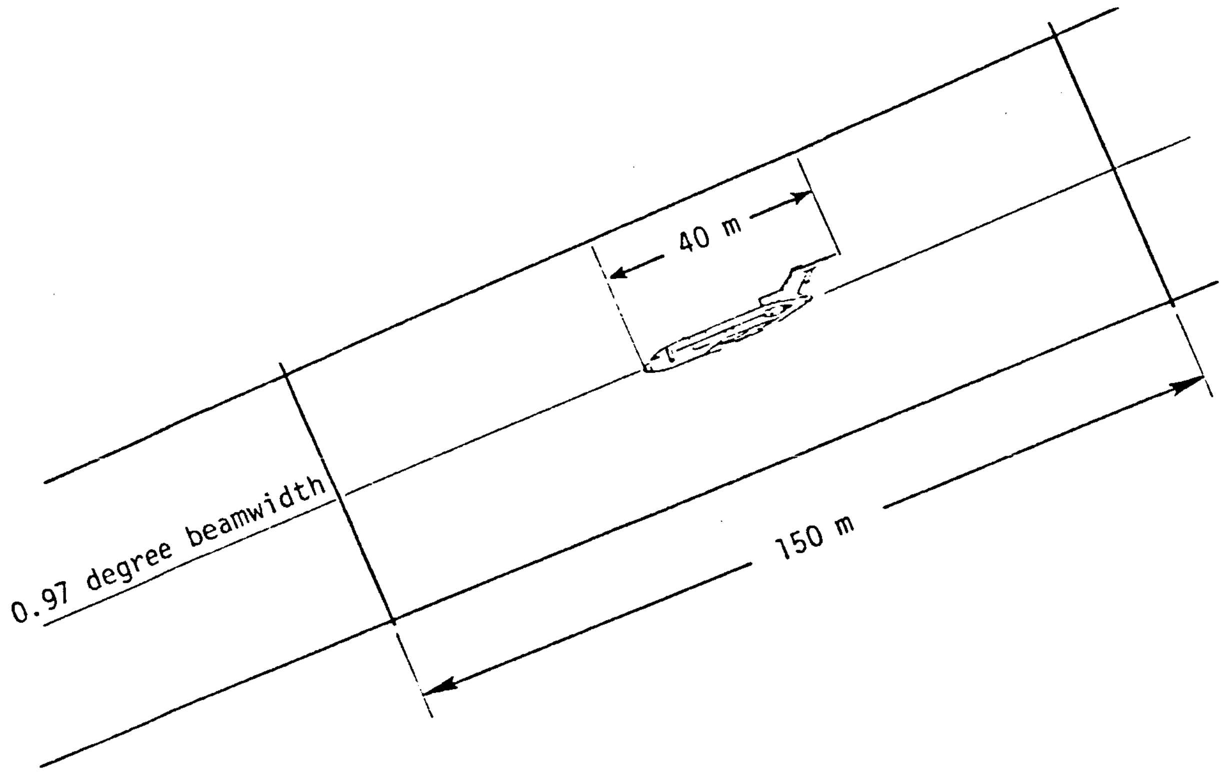
An example of the analyses of the B-57 Gust Gradient data for Flight 6, Run 3 is given in the appendix to this paper. This is the format in which the data will be available. For further details on the data, contact Dennis Camp at NASA Marshall Space Flight Center.

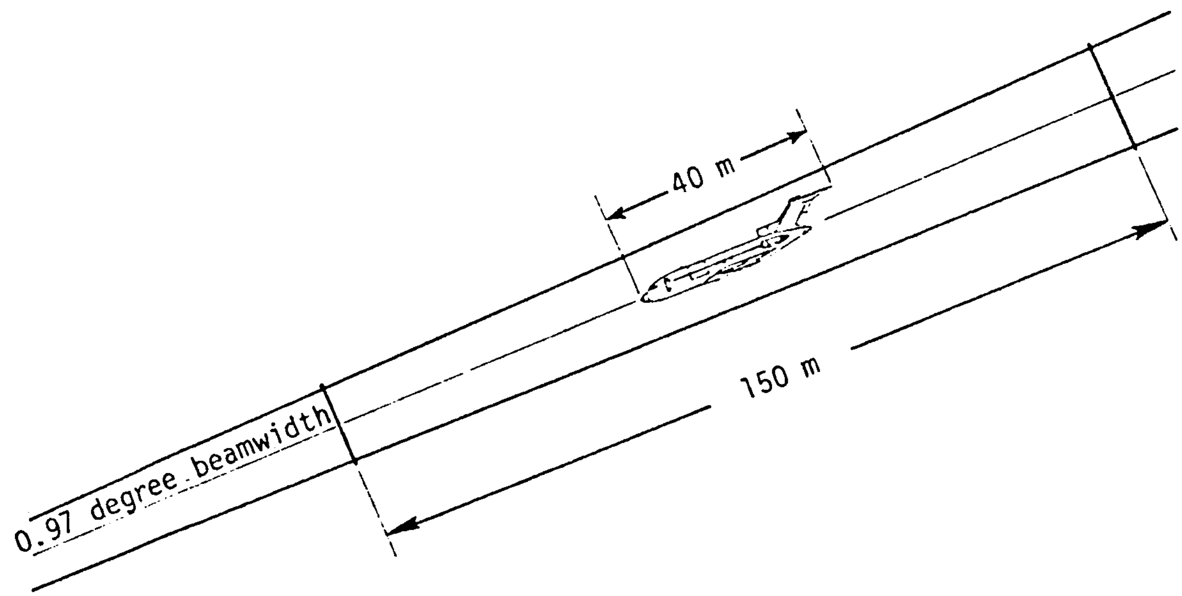
I would like to address the subject of modeling turbulence for use with the JAWS wind shear data sets. The present FAA AC 120-41 wind shear models (reference 1) are quasisteady wind models. FAA recommends superimposing upon these winds a Dryden spectrum model of turbulence. For the JAWS data, we have to decide whether this approach is adequate or whether we need to analyze and model turbulence differently.

The question is why do we need turbulence for the JAWS data set? In looking at scaled drawings of a B-727-type aircraft inside of a typical volume element of the size sensed by the Doppler radar (figure 1), the volume element is seen to engulf the airplane. A typical volume element or range gate probed by a Doppler radar is about 150 m in length and spreads out cylindrically with distance from the radar. Any atmospheric motion less than the volume element in size is averaged out of the radar signal. In addition, the data are transferred to a spatial grid that is about 200 m by 200 m. The 200 m grid size scaled relative to the dimensions fo various types of aircraft is shown in Figure 2. One observes that even the biggest airplane, the B-747, occupies only a small part of the volume element. Thus, there are atmospheric disturbances going on within the volume element that are relatively large compared to the aircraft, but that are smoothed out by the averaging process.

For discussion purposes, say that the typical grid scale for the JAWS data set is 200 m. The spatial sampling frequency is thus 1/200 m^{-1}. The Nyquist frequency is then 1/400 m^{-1}. Assuming an airspeed of 80 m/s, the temporal frequency is then approximately 0.2 Hz. This means that any disturbances less than the grid spacing in spatial scale, or higher than roughly 0.2 Hz frequency, is not contained in the JAWS data set. Figure 3 shows that the phugoid frequency is typically less than the 10^{-2} Hz, so most effects on the order of the phugoid frequency are contained in the JAWS data set. The short period frequency are between 10^{-2} and 0.5 Hz. Therefore, some short period disturbances are contained in the JAWS data. For simulation of structural effects, however, high-frequency turbulence must be superimposed upon the JAWS data. In Figure 3, the one-dimensional von Karman longitudinal θ_{11}, and lateral, θ_{22}, spectra are plotted along with the three-dimensional energy spectrum, E. It is observed that for very large length scales, there is not much turbulence energy beyond the JAWS cutoff frequency. The question is how to model turbulence contained in the higher frequency range.



a) Range gate at 150 m (490 ft) above runway



b) Range gate at 50 m (160 ft) above runway

Figure 1. Approximate size of B-727-100 type aircraft relative to a range gate volume element.

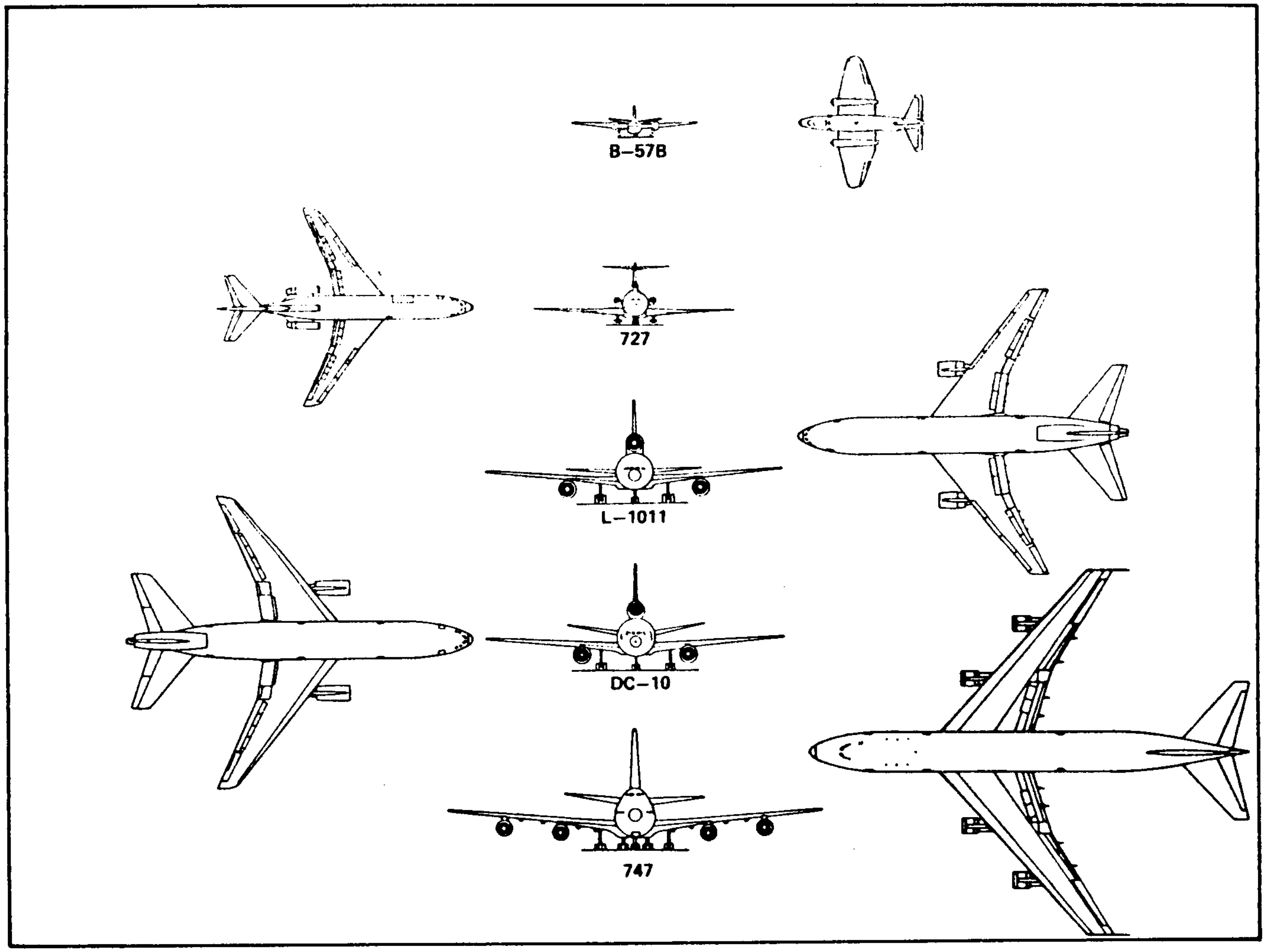


Figure 2. Comparison of JAWS sizes of July 14 grid size with various size aircraft.

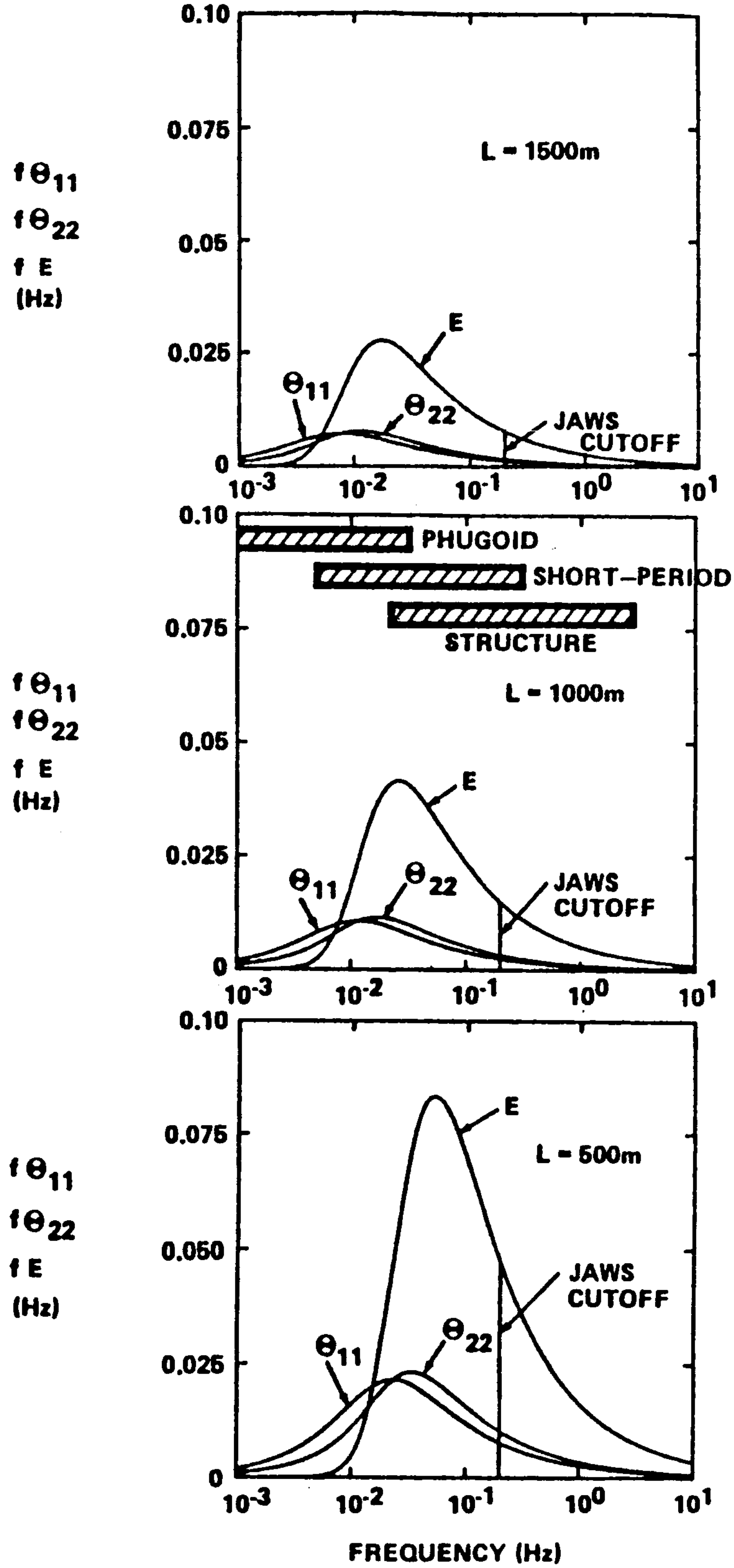


Figure 3. Comparison of significant frequencies with JAWS cutoff frequency.

The effect of turbulence is not likely to appreciably influence the trajectory of the aircraft; however, it may have appreciable effect on handling qualities and pilot workload.

Typically, turbulence models use the point mass assumption that the aircraft is totally immersed in the turbulence. The point mass assumption is sometimes enhanced by assuming a linear gradient of gust velocities. This sometimes leads people to believe that the linear gradients of the JAWS data are also included in their wind shear models. The two gradient terms are different things, however, as will be described later. Also models have been developed which provide spanwise gust gradients across the airfoil. These could be used in simulation but are relatively complex mathematical models and are not likely in use at this time. Warren Campbell at Marshall Space Flight Center has proposed a three-dimensional turbulence model (reference 2).

The conventional method of simulating turbulence is to pass a computer-gererated Gaussian white noise through a filter. The filter shapes the random output signal such that it has certain statistical properties characteristic of the atmospheric turbulence to be simulated. Generally, the two statistical parameters which are reporduced are the turbulence intensity and the frequency content through the turbulence energy spectrum. The Dryden spectrum is most commonly used. It is well established that the von Karman spectrum fits the turbulence experimental atmospheric data better than the Dryden spectrum; however, the Dryden is much easier to handle mathematically. Typically, the output of a turbulence simulation results in a Gaussian distribution of the velocity fluctuations. Again, it is well established that atmospheric turbulence is not Gaussian; however, this approximation is generally acceptable. Turbulence simulation models exist that will provide non-Gaussian turbulence, but they are mathematically complex. Thus, simulated turbulence with Gaussian velocity distribution, Dryden spectra, and specified turbulence intensity is universally used because it is the simplest to implement. This simple model provides the three fluctuating velocity components and treats the airplane as a point mass. Figure 4 illustrates schematically, however, that the point mass model inherently treats only one-dimensional wind variation in the flight direction.

As the figure further illustrates, however, turbulence is typically three-dimensional. To account for spatial variation in turbulence, several turbulence modelers have gone to the idea of linear gust gradients. The typical parameters entering the turbulence models are shown in Figure 5. The turbulence model provides the uniform gust W_x, W_y, W_z and linear gradients of gust velocity p_g, q_g, and r_g. These gradient terms create rolling, pitching and yawing moments. It should be noted, however, that these terms are different from the wind shear terms discussed earlier. The effect is very similar but the gradient values are of defferent magnitudes. Moreover, if you turn off the turbulence simulation, the effects of the linear gradient terms will disappear. The flow chart for computing random turbulence with linear gust gradients is shown in Figure 6. The question is whether turbulence generated in this manner should be superimposed on the JAWS wind fields and, if so, how turbulence of the same scale length, which already exists in the JAWS data, is to be filtered out.

Another issue relative to turbulence simulation is whether to generate the turbulent wind fluctuations in the body frame or the earth frame of reference. If you consider only the translational velocity (i.e., w_x, w_y, w_z) components and

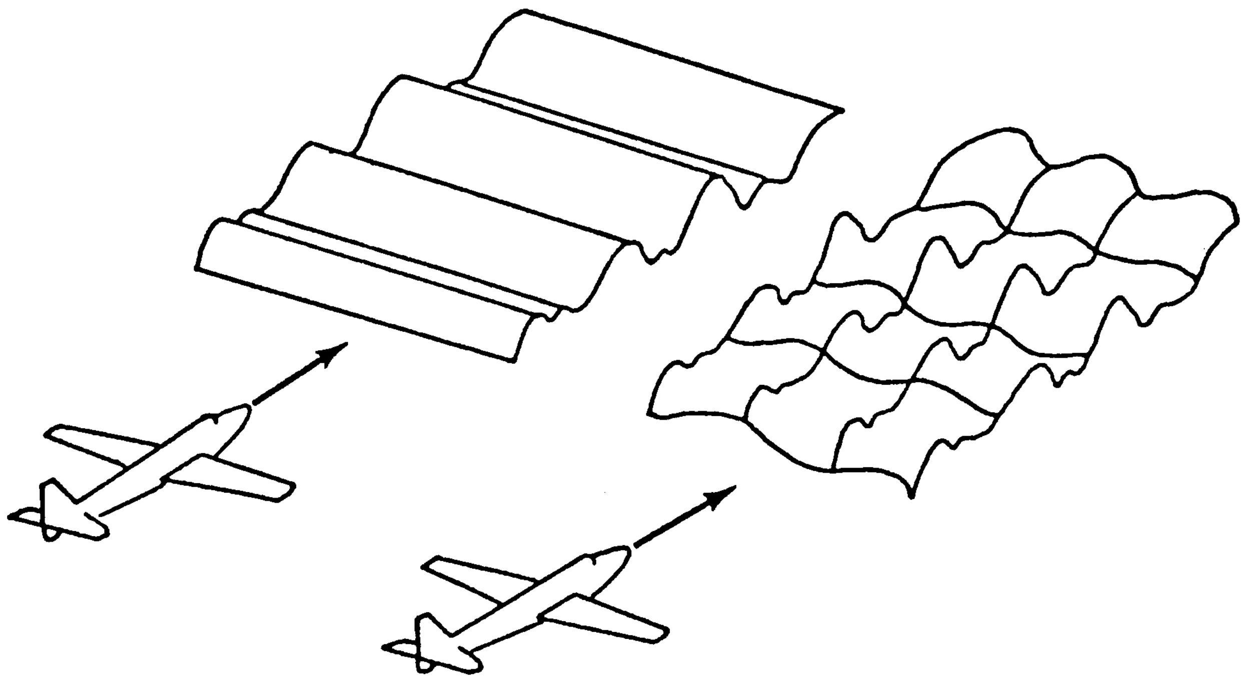


Figure 4. Assumptions of turbulence simulation.

- Uniform Gust Immersion

  w_x, w_y, w_z

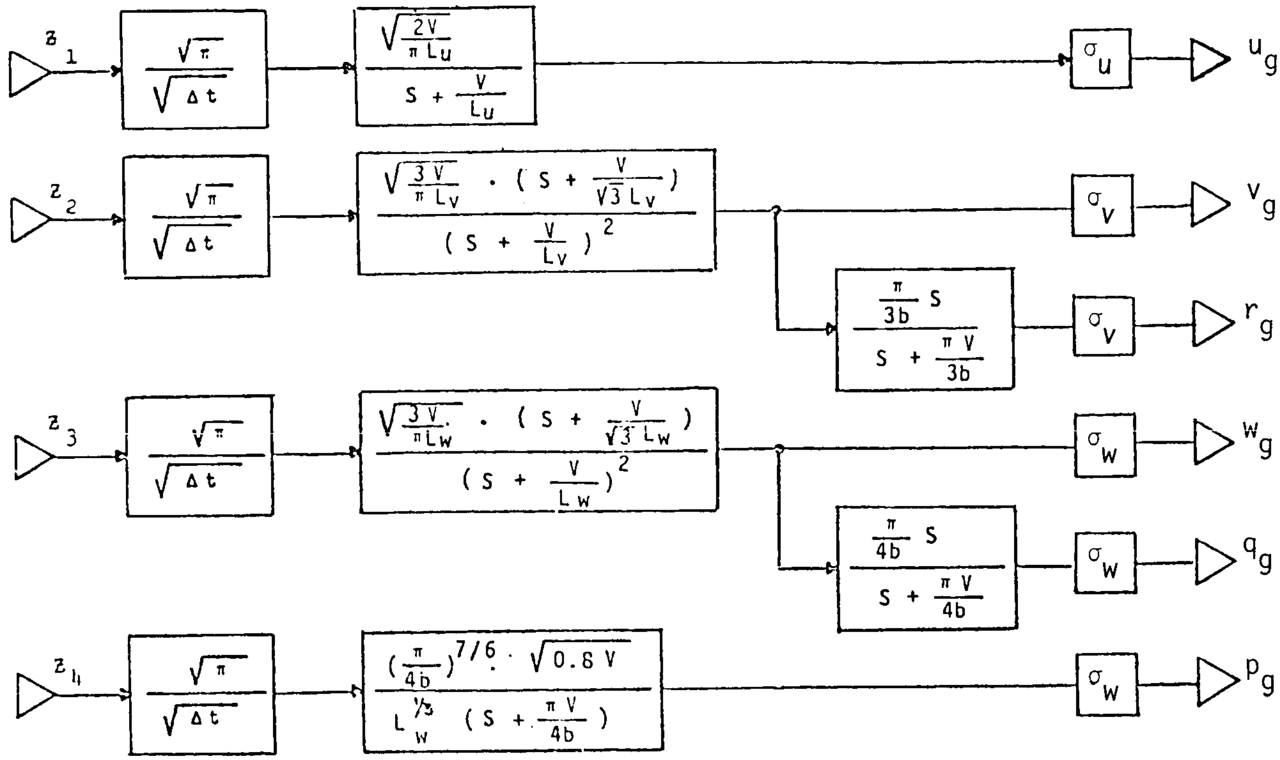
- Linear Gradients of Gust Velocities

$$p_g = -\frac{\partial w_z}{\partial y}$$

$$q_g = \frac{\partial w_z}{\partial x} = -\dot{\alpha}_g$$

$$r_g = -\frac{\partial w_y}{\partial x} = \dot{\beta}_g$$

Figure 5. Parameters from turbulence models with distributions of gusts over aircraft (from MIL-F-8785B, reference 3).



z_i = independent, digital, Gaussian, unit RMS white noise

Figure 6. Random turbulence simulation with linear gust gradients.

generate these in the earth coordinate system based on appropriate wind models, add them to the mean winds or quasi-steady winds, and transfer the total wind speed components back to the body axis, you should have no trouble. Now consider the rotational turbulence componens shwon in Figure 6, p_g, q_g, and r_g. In computing these components, you must be careful. If a spectrum for turbulence gradients is used (see Figure 6) then your analysis will depend upon how it was measured. Since q_g and r_g are correlated with w_g and v_g, respectively, the w_g and v_g components must be obtained by transforming from the earth frame of generation to the body frame before q_g and r_g are computed.

Figure 4 clearly indicates that the turbulence is not uniform over the airfoil although the basic models currently in use make this assumption. Some attempts at modeling spanwise gust variation have been investigated. One approach is illustrated in Figure 7. Basically, this approach consists of calculating the lift as a function of time by using the indicial function n(y,t). The indicial function gives the lift response of the wing due to a sinusoidal gust occurring at position y along the wing, and at corresponding time, t. After carrying out the operations shown in Figure 7, you end up with the spectrum of the lift. The expression of the spectrum of the lift, however, contains the cross-correlation or two-point spectrum. This is normally developed assuming isotropic homogenous turbulence. The reason for the NASA B-57 Gust Gradient Program is to provide additional information relative to the two-point spectrum or distribution of gusts acress the airfoil. By using the spectrum of lift to model your filter and passing a white noise through this filter, you can generate a random lift with gust variations across the wing as a function of time. Similar approaches could be made for rolling moments, yawing moments, etc. This approach is very time consuming, however, and I do not believe that it is used in any operational flight simulator at present. Moreover, the spectrum is not only a function of the wind or atmospheric conditions, but also of the airplane dynamics, or of n(y,t), which is the lift characteristic of the airfoil.

A second approach to incorporate spanwise turbulence gradients is to utilize the gust gradient data with strip theory. The previous model, of course, is also based upon strip theory; but in the approach addressed here, finite elements are used and the assumption of isotropic homogeneous turbulence eliminated. Figure 8 shows how the wind is distributed across the airfoil. The velocity at each element varies with time. Thus, at any incident of time, we have a random distribution of the wind which is used to calculate the lift by the straightforward strip theory approach. With the gust gradient data, we have divided the wing into three panels using the measured relative wind speed at both wing tips and at the nose boom to calculate the lift. With this approach, we have calculated yawing and rolling moments which the aircraft experienced during a data gathering flight based on the measured values. The results show that the yawing and rolling moments can be quite high due to the non-uniform wind distribution. We are streamlining this approach for simulator applications. The results would give us teh rolling and yawing moments caused by turbulence of a smaller scale than that included in the JAWS data sets. Basically, what we are doing at this time is utilizing the test flight data. The relative wind, speed, and angle of attack are input to the strip theory computer program, and lift, drag, yaw, and roll moments are computed. These values are then input into the aerodynamic forces in our six-degree-of-freedom aircraft motion computer program, and the flight path is calculated. The results are then compared with the actual measured aircraft performance to determine how valid is the strip theory computational procedure. There is always a

$$L(t) = \int_{-\infty}^{\infty} \int_{-b/2}^{b/2} h(t,y) w_z(V(t - t_1), y) dy dt_1$$

Assume

$$h(t,y) = h_t(t) h_y(y)$$

$$\phi_L(\omega) = |H_t(\omega)|^2 \phi_{w_{ze}}(\omega)$$

$$\phi_{w_{ze}} = \frac{1}{b} \int_0^b \Gamma(\eta) \tilde{\phi}_{w_z}(\omega, \eta) d\eta$$

where

$$\tilde{\phi}_{w_z}(\omega, \eta) = \frac{1}{V} \int_{-\infty}^{\infty} e^{-i\omega\xi/V} \psi_{w_z}(\sqrt{\xi^2 + \eta^2}) d\xi$$

Figure 7. Spectral method for spanwise gust variation.

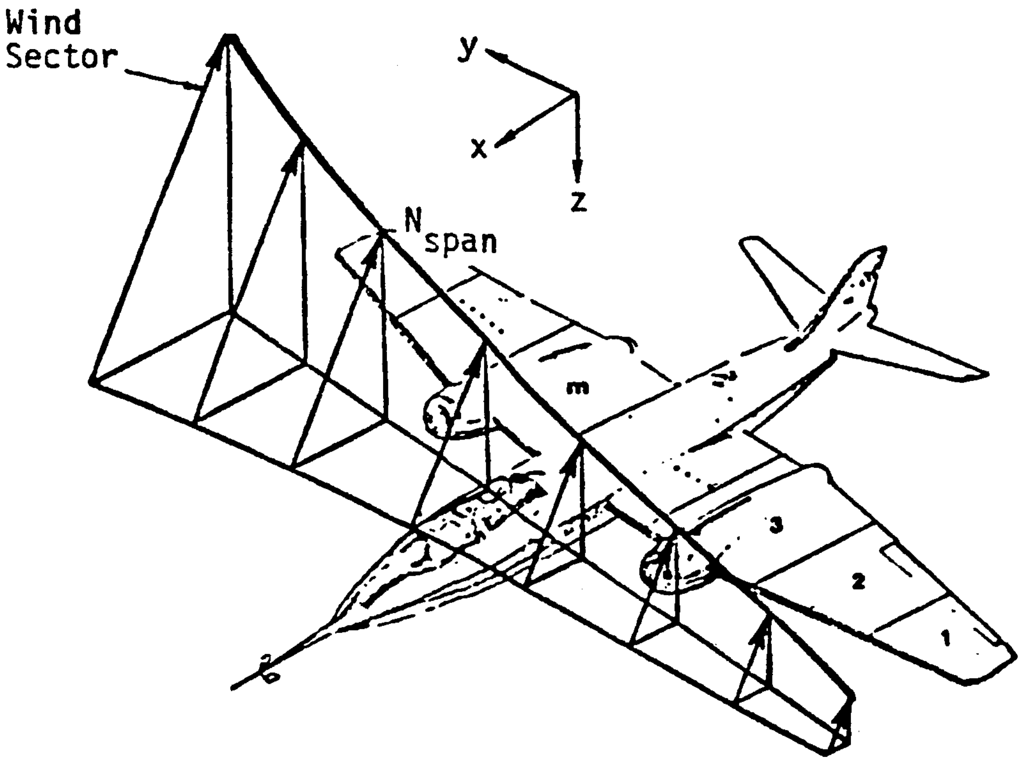


Figure 8. Gust variation over the wing span using finite elements.

$$u_i(X,Y,Z,t) = \bar{U}_i(X,Y,Z,t) + \sigma_i(X,Y,Z,t) * W_i(X,Y,Z)$$

$u_i(X,Y,Z,t)$ ARE THE SIMULATED WINDS
$\bar{U}_i(X,Y,Z,t)$ ARE THE ENSEMBLE AVERAGE WINDS
$\sigma_i(X,Y,Z,t)$ ARE THE ENSEMBLE AVERAGE GUST INTENSITIES
$W_i(X,Y,Z)$ IS "FROZEN" TURBULENCE

ADVANTAGES

* 3–D TURBULENCE AND GUST GRADIENTS
* COMPATIBILITY WITH DOPPLER RADAR DATA
* ABILITY TO SIMULATE A WIDE RANGE OF ATMOSPHERIC PHENOMENA

DISADVANTAGES

* REQUIREMENT FOR A LARGE DATA BASE
* 1–D SPECTRA ARE NOT AS ACCURATE AS FOR A 1–D SIMULATION

Figure 9. Three-dimensional turbulation simulation.

problem of control inputs in making such a comparison. The gust gradient aircraft has now been equipped with control input measuring devices, and hence, we can make comparisons of computed control inputs relative to actual control inputs by the pilot. On a statistical basis, we are getting excellent agreement between the measured and computed results. The development of this system for utilization in operational flight simulators will provide more realistic simulation of roll and yaw motions.

A final model of turbulence proposed for imposing the small scales of turbulent motion into the JAWS data sets is a three-dimensional turbulence model developed by Warren Campbell (reference 2). The concept inputs three-dimensional white noise into a filter. The filter is a three-dimensional spectrum model which can be either the von Karman or the Dryden spectrum. Campbell utilizes the von Karman spectra, which results in homogeneous isotropic turbulence, but fully three-dimensional. Application of the model to the JAWS data is based on establishing a smaller grid within each grid element of the JAWS data set. As an illustration, Campbell has utilized 10 m grid spacings for his turbulence model (within the 200 m by 200 m JAWS grid, you impose internally a 10 m by 10 m grid). Turbulence, which Campbell refers to as frozen (i.e., not varying with time, but varying spatially) is computed for each grid point within the large JAWS grid volume element.

Figure 9 illustrates the three-dimensional turbulence simulation concept. The quantity σ_i is the turbulence intensity which can vary spatially. This value is unknown and must be determined experimentally. Analysis of the Doppler radar second moment is being carried out to determine if these values of the turbulence intensity can be determined. From the preliminary results, it is clear that the turbulence intensity will vary appreciably around the downdraft section of the flow and probably behave similarly to other turbulence models far from the center of the downdraft. The nature of turbulence associated with a microburst and its determination from the existing JAWS data are issues which we may wish to address in the discussion sessions.

Returning to the issue of what turbulence to superimpose on the JAWS data, a number of models are available as described, (see Figure 10). There are two extremes, and probably somewhere in between is a good solution. The simple model is the Gaussian Dryden spectrum model; again, we know is not correct, but is easy to use mathematically, and most simulators probably have this system already incorporated.

One of the problems, however, in using any turbulence model to superimpose on the wind shear data is that the JAWS data already incorporates considerable low-frequency turbulence. Therefore, the low frequency must be filtered out of the superimposed turbulence generated by a model which will contain all frequencies. The question is how is this best done? One approach is simply to run the simulated turbulence through a filter that cuts out everything that is less than 200 m in scale.

An alternate approach is to use a highly complex model such as Campbell's model. Here you generate blocks of turbulence which are input to the JAWS data set and you fly through these moving the blocks as you proceed. There are a couple of problems, however: one is realistic values of the turbulence intensity which, hopefully, we can get from the JAWS Doppler radar second moment data. The second problem is length scale. The question is what scale of turbulence does

- Simple Model -- FAA AC No. 120-41
  - Dryden spectra
  - Intensities and length scale are functions of altitude
- Highly Complex Model -- Campbell's 3-D
  - Homogeneous isotropic
  - Incorporate all correlations
  - Blocks stacked within JAWS grid volume

Figure 10. Possible turbulence models for JAWS data set.

one utilize in the simulation model? We do not have a good handle on length scales for turbulence associated with a microburst. Thus, a number of questions remain unanswered relative to developing a turbulence model to superimpose upon the quasi-steady JAWS data winds.

The conclusions, then, are as follows. 1) Turbulence of length scales less than the JAWS grid size should be superimposed on wind fields to provide correct simulation of pilot workload. Also, to correctly simulate the short-period aircraft response as well as structural response, this smaller scale turbulence is necessary. 2) To develop a realistic and effective turbulence model, research is required. The research should address the interpretation of turbulence intensity and information relative to turbulence length scale from Doppler radar second moments. How to establish a meaningful length scale is a major issue which must be addressed from a research point of view. Finally, a research study to investigate the trade-off between degrees of complexity in models and computer capabilities as well as the fidelity of the models is required.

REFERENCES

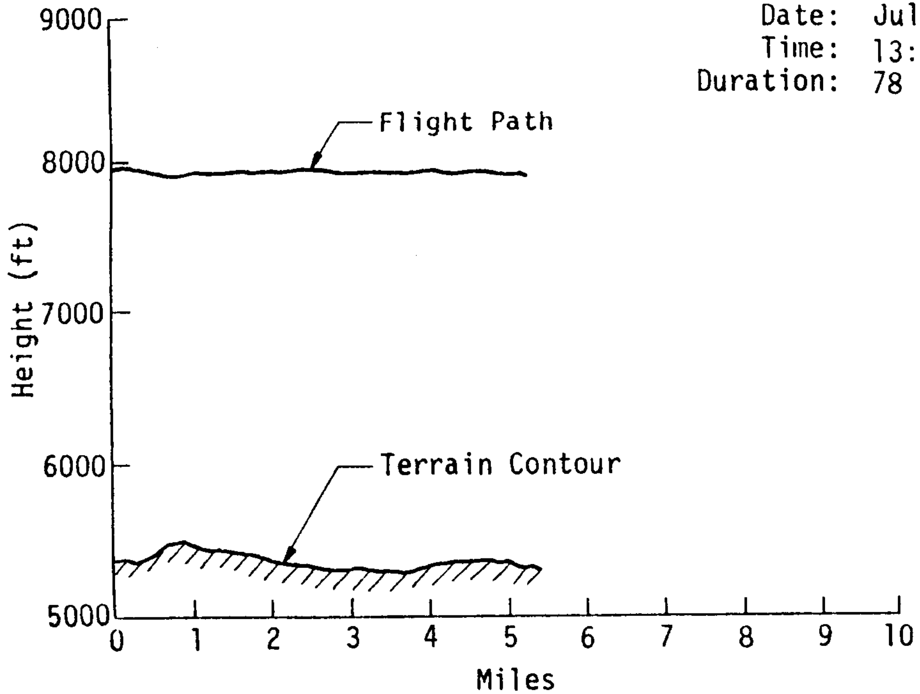
1. Criteria for Operational Approval of Airborne Wind Shear Alerting and Flight Guidance Systems. Advisory Circular 120-41, Federal Aviation Administration, November 1983.

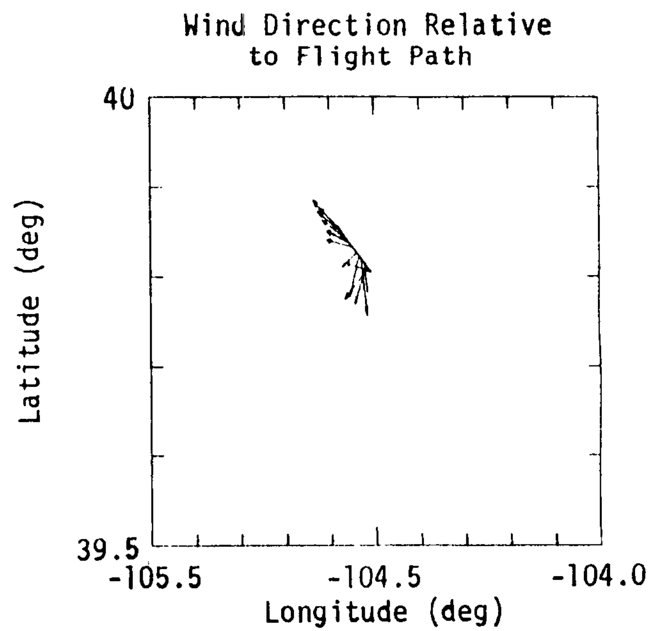
2. Campbell, Warren C.: A Spatial Model of Wind Shear and Turbulence for Flight Simulation. NASA TP-2313, 1984.

3. Military Specification - Flying Qualities of Piloted Airplanes. MIL-F-8785C, November 5, 1980.

FLIGHT PATH INFORMATION: FLIGHT 6, RUN 3

Date: July 14, 1982
Time: 13:50:05
Duration: 78





AVERAGE PARAMETERS

Flight 6, Run 3, JULY 14, 1982

I. Mean Airspeed (m/s)

V_L	V_C	V_R
111.5	110.7	112.4

II. Standard Deviation of Gust Velocities (m/s)

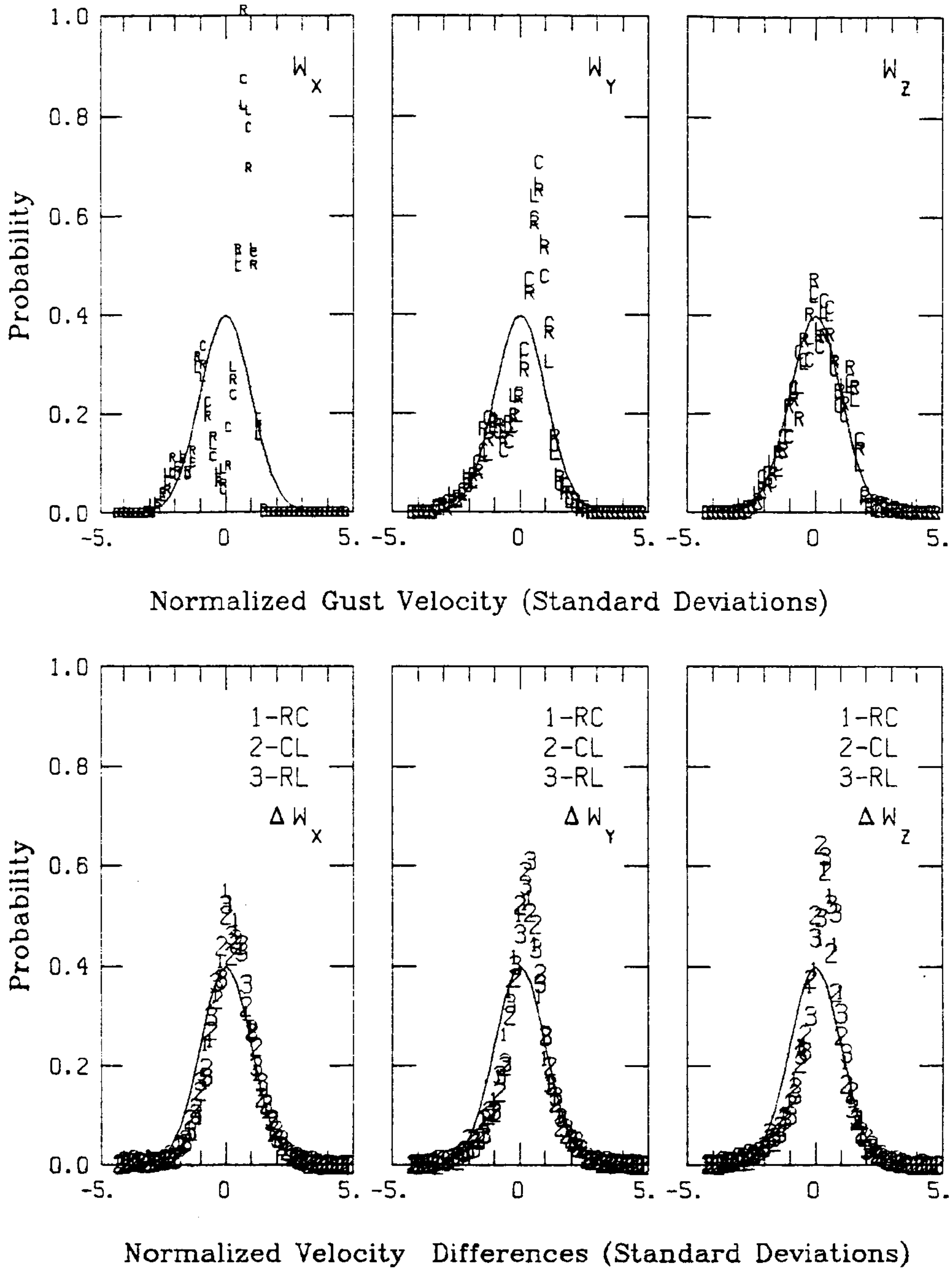
$\sigma_{W_{XL}}$	$\sigma_{W_{XC}}$	$\sigma_{W_{XR}}$
3.75	3.68	3.73
$\sigma_{W_{YL}}$	$\sigma_{W_{YC}}$	$\sigma_{W_{YR}}$
1.77	1.81	1.73
$\sigma_{W_{ZL}}$	$\sigma_{W_{ZC}}$	$\sigma_{W_{ZR}}$
2.10	2.04	2.24

III. Standard Deviation of Gust Velocity Differences (m/s)

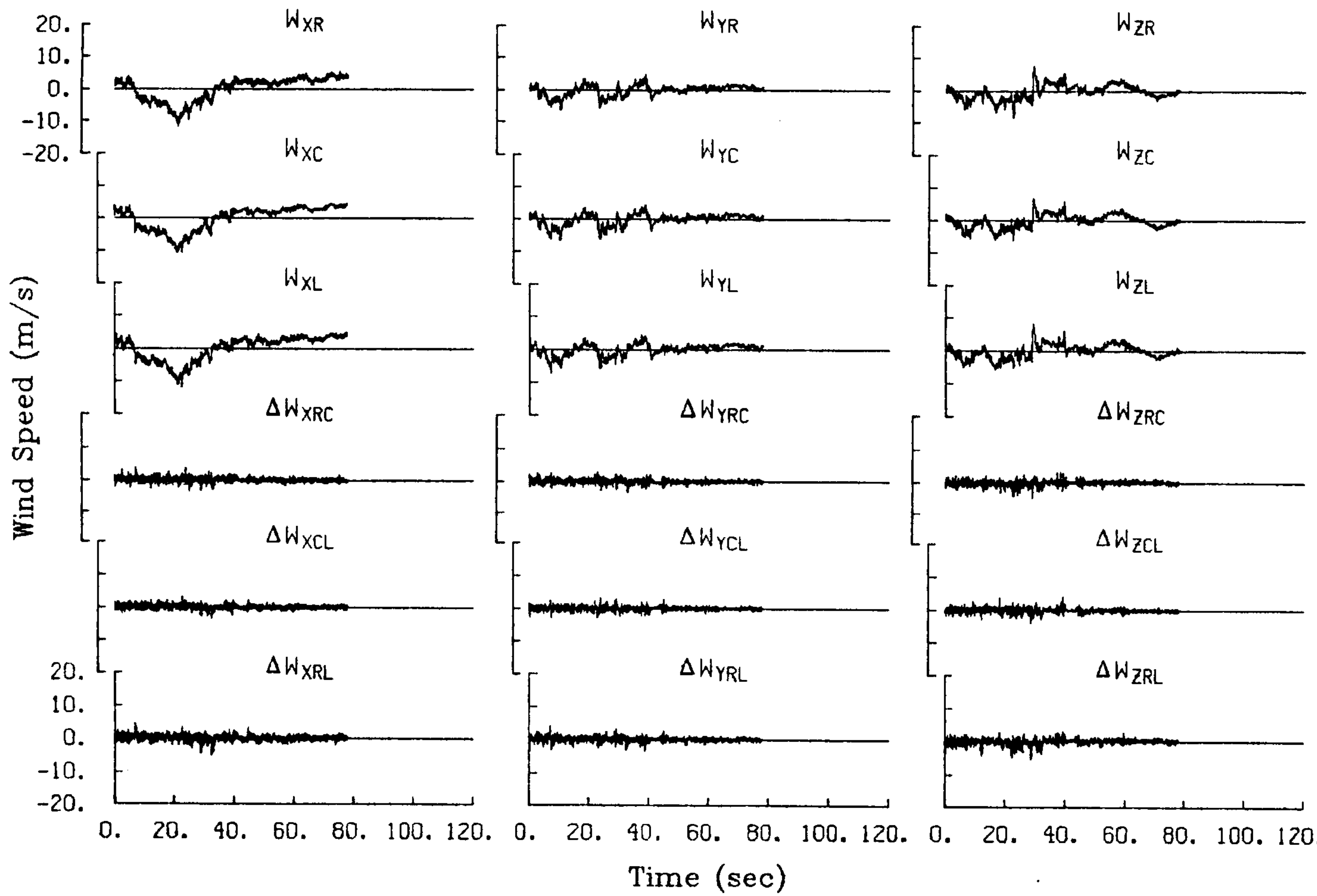
$\sigma_{\Delta W_{XCL}}$	$\sigma_{\Delta W_{XRC}}$	$\sigma_{\Delta W_{XRL}}$
0.64	0.65	0.82
$\sigma_{\Delta W_{YCL}}$	$\sigma_{\Delta W_{YRC}}$	$\sigma_{\Delta W_{YRL}}$
0.60	0.59	0.65
$\sigma_{\Delta W_{XCL}}$	$\sigma_{\Delta W_{ZRC}}$	$\sigma_{\Delta W_{ZRL}}$
0.66	0.72	0.83

IV. Integral Length Scale (m).

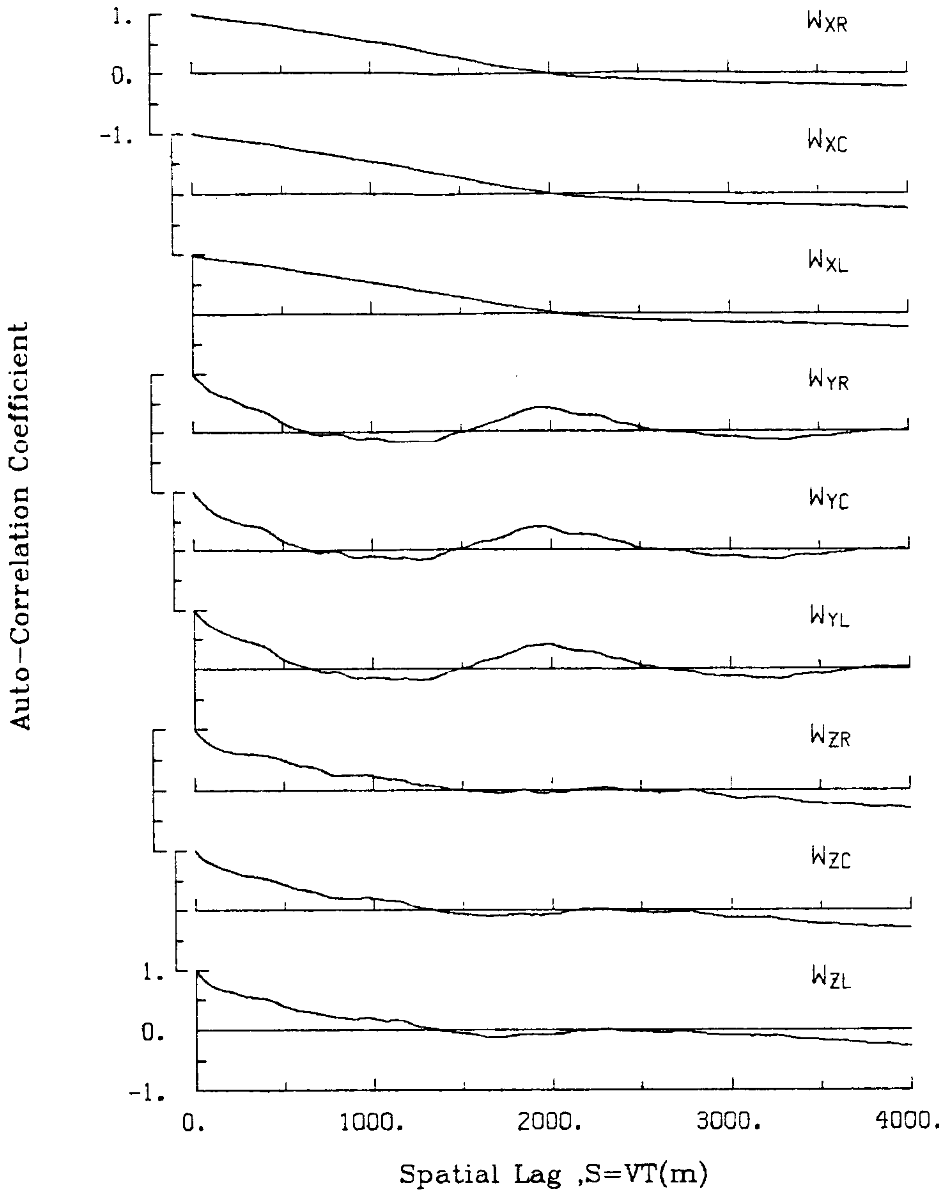
$L_{W_{XL}}$	$L_{W_{XC}}$	$L_{W_{XR}}$
1042	1043	1038
$L_{W_{YL}}$	$L_{W_{YC}}$	$L_{W_{YR}}$
554	541	559
$L_{W_{ZL}}$	$L_{W_{ZC}}$	$L_{W_{ZR}}$
940	976	1050



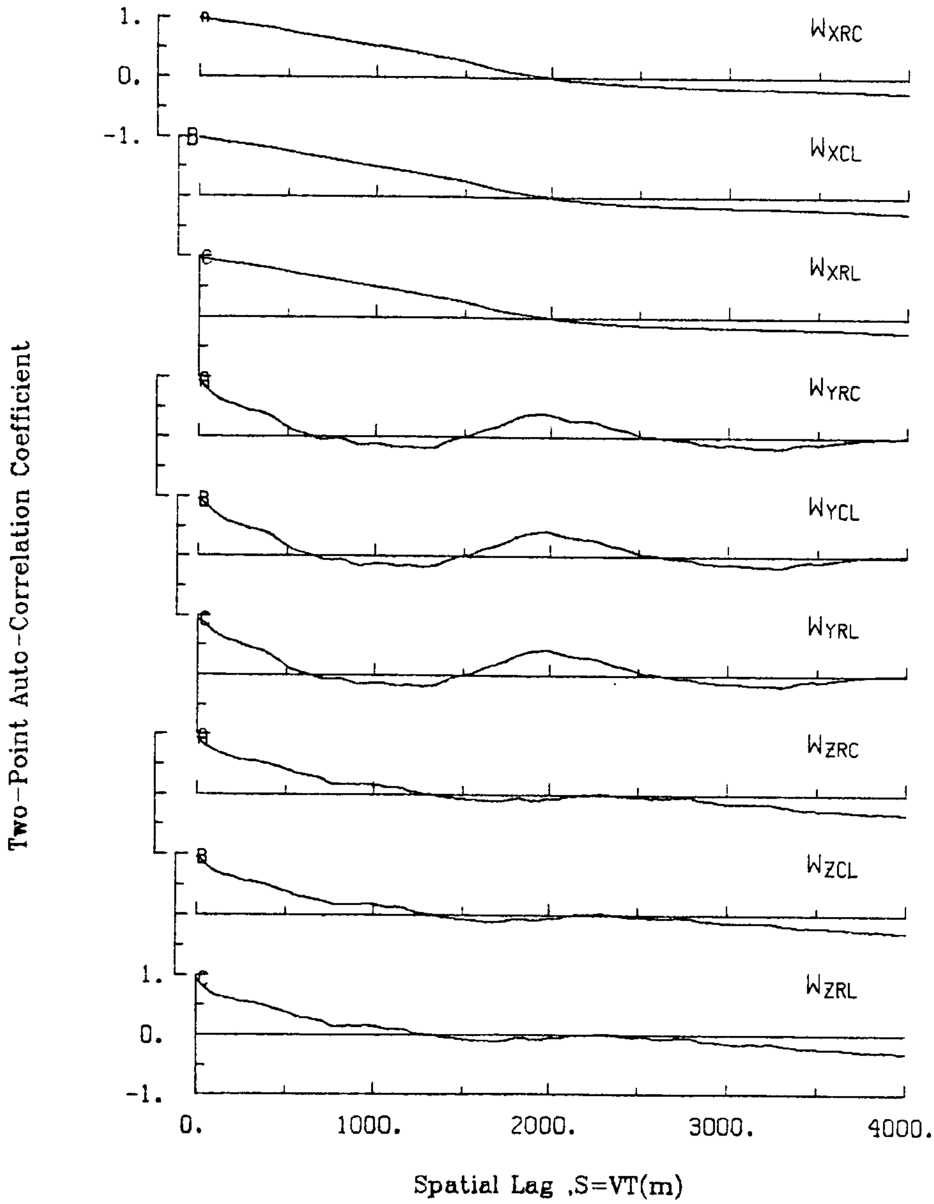
PROBABILITY DENSITY FUNCTION FOR GUST VELOCITIES AND THEIR DIFFERENCES. R= right , C= center , L= left , Flight 6, Run 3.



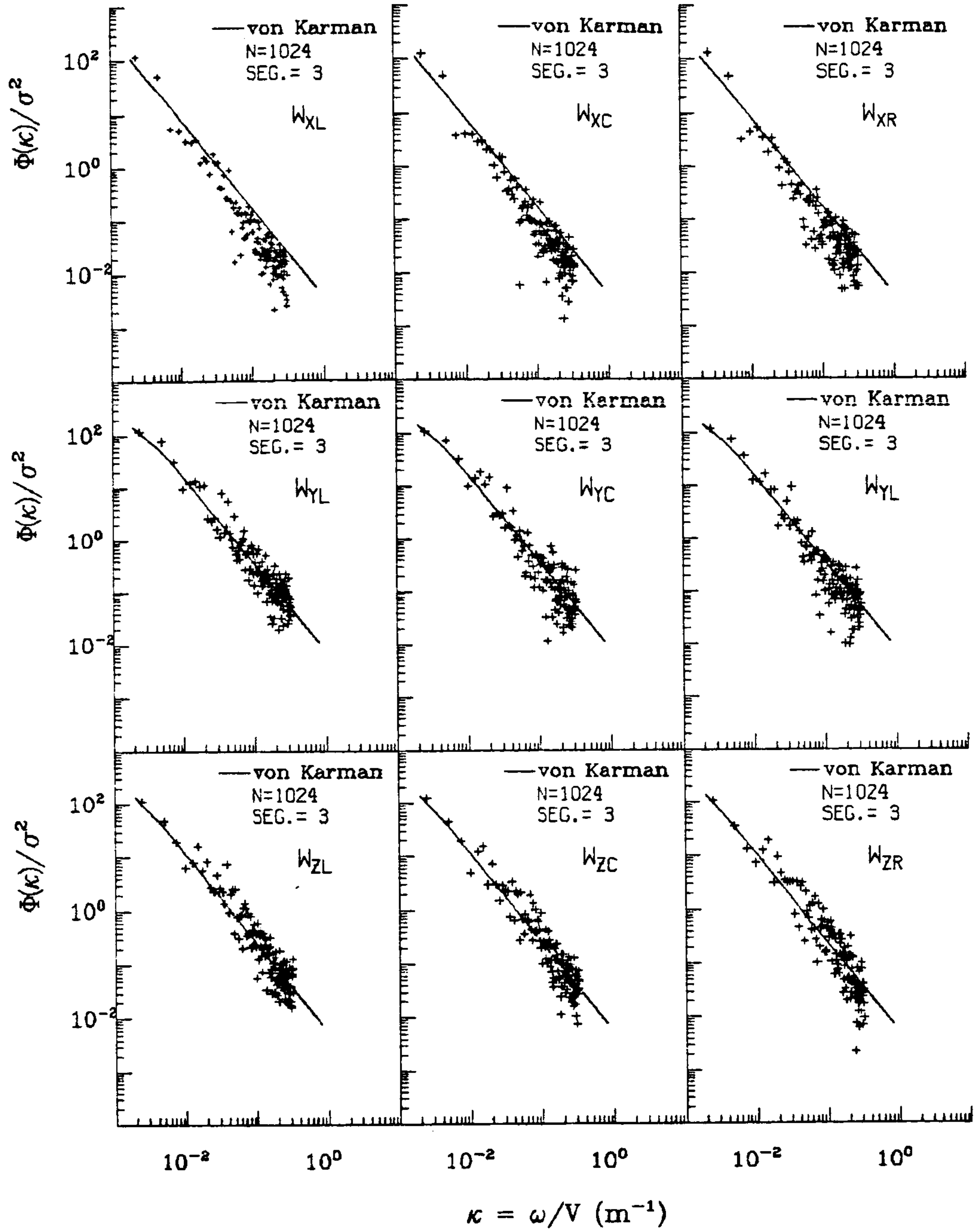
TIME HISTORIES OF THE GUST VELOCITIES AND THEIR DIFFERENCES,
Flight 6, Run 3.



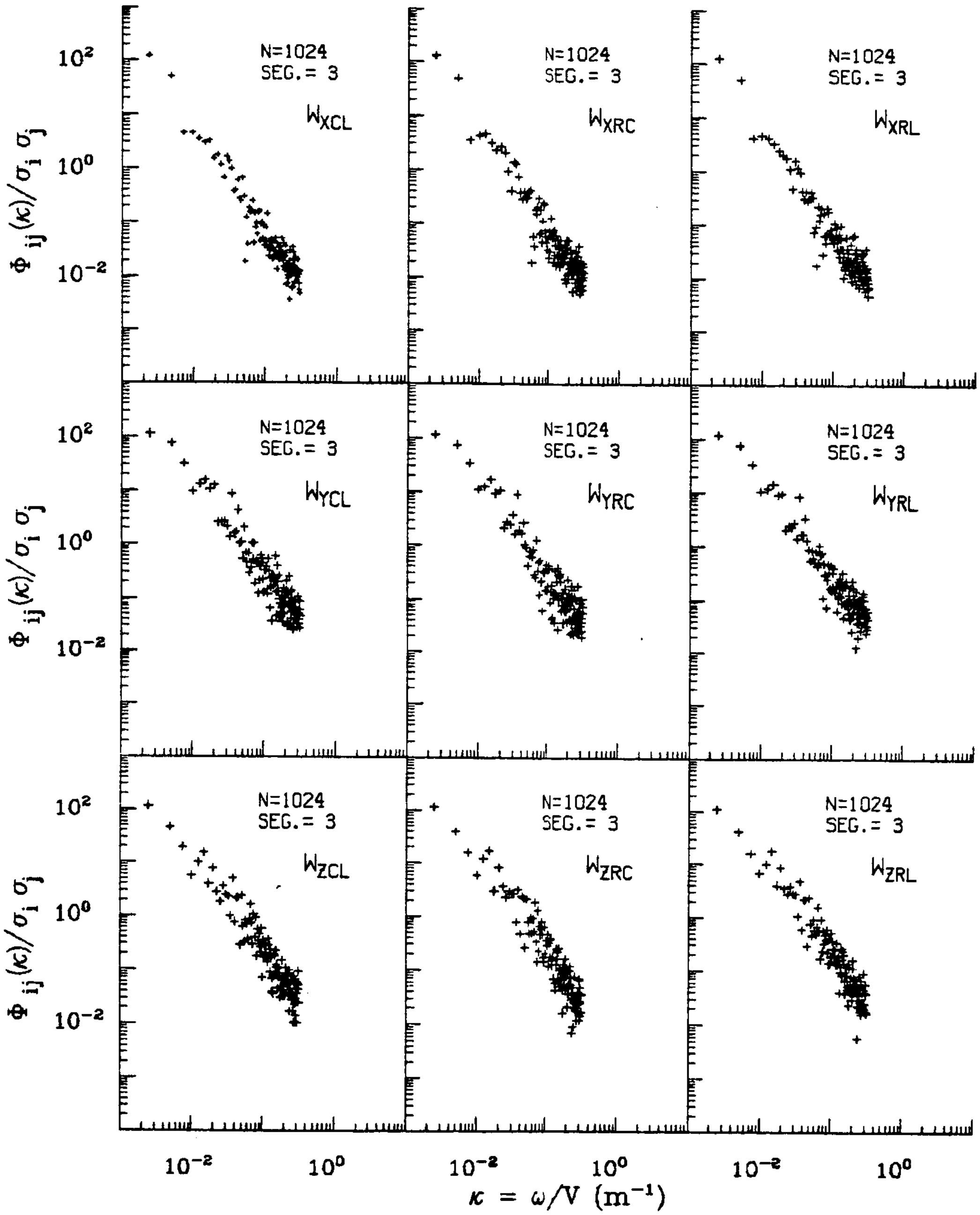
SINGLE-POINT AUTO-CORRELATION OF GUST VELOCITIES,
Flight 6, Run 3.



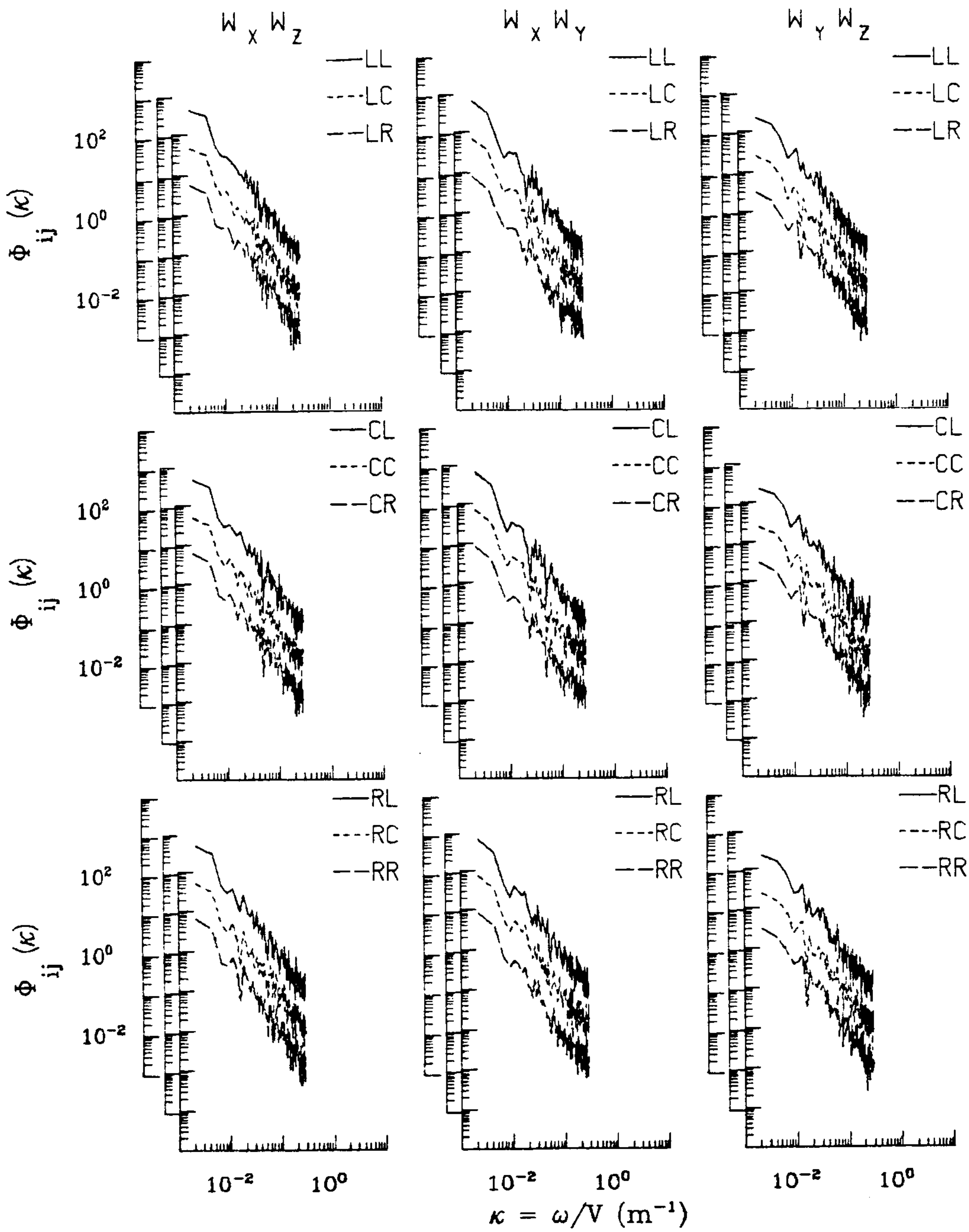
TWO–POINT AUTO–CORRELATION COEFFICIENT
lines computed from Taylor s hypothesis, A and B spatial correlation between center and wing tips, C spatial correlation between wing tips,
Flight 6, Run 3.



NORMALIZED AUTO-SPECTRA OF GUST VELOCITIES, Flight 6, Run 3.



NORMALIZED TWO-POINT AUTO-SPECTRA OF GUST VELOCITIES, Flight 6, Run 3.



TWO–POINT CROSS–SPECTRA OF THE GUST VELOCITIES, Flight 6, Run 3.

ORIGINAL PAGE IS
OF POOR QUALITY

RANGE OF ALL PARAMETERS MEASURED
Flight 6, Run 3

START TIME = 49805.4844 STOP TIME = 49883.5094

CHANNEL	UNITS	HIGH	LOW	MEAN	RMS	POINTS
2 PHI DOT	RAD/SEC	.072	-.088	-.00324	.02078	3121
3 ACCL N CG	G UNITS	1.627	.642	.99422	.99850	3121
4 THETA DOT	RAD/SEC	.037	-.045	.00481	.01095	3121
5 THETA	RAD	.094	.031	.06292	.06434	3121
6 PHI	RAD	.041	-.069	-.00889	.02096	3121
7 PSI 1	DEGREES	313.321	308.297	310.69637	310.69764	3121
8 DEL PSI 1	DEGREES	2.904	-1.857	.51978	1.02301	3121
9 PSI 2	DEGREES	314.988	310.060	312.55654	312.55775	3121
10 DEL PSI 2	DEGREES	2.874	-1.802	.51022	1.01485	3121
11 ACCL N LT	G UNITS	2.020	.160	1.01168	1.02621	3121
12 ACCL N RT	G UNITS	1.859	.182	1.02835	1.04275	3121
13 ACCL X CG	GUNITS	.139	.032	.06434	.06518	3121
14 ACCL Y CG	G UNITS	.175	-.159	.00796	.05271	3121
15 ALPHA CTR	RAD	.058	-.054	-.01048	.01490	3121
16 BETA CTR	RAD	.036	-.072	-.02107	.02740	3121
17 TEMP I	DEG F	107.798	106.899	107.33032	107.33056	3121
18 TEMP P	DEG F	90.006	89.647	89.83471	89.83472	3121
19 ACCL Z INS	G UNITS	1.633	.620	1.00459	1.00892	3121
20 ALPHA RT	RAD	.068	-.060	-.00229	.01282	3121
21 BETA RT	RAD	.063	-.035	.01447	.02156	3121
22 ALPHA LT	RAD	.069	-.039	.00071	.01119	3121
23 BETA LT	RAD	.021	-.085	-.02642	.03106	3121
24 PSI DOT	RAD/SEC	.035	-.027	.00346	.01146	3121
25 TEMP TOT	DEG C	29.514	28.240	28.94907	28.95259	3121
26 QC LT	PSID	.975	.758	.82327	.82447	3121
27 QC CTR	PSID	.944	.751	.81163	.81273	3121
28 QC RT	PSID	.993	.763	.83729	.83843	3121
29 PS	PSIA	10.979	10.680	10.95411	10.95412	3121
30 TEMP IRT	DEG C	24.966	13.439	20.73977	20.83180	3121
31 D TO G	METERS	8742922.214	8737460.433	**********************		3121
32 B TO D	DEGREES	80.291	80.229	80.26050	80.26050	3121
33 LONG	DEGREES	-105.006	-105.082	-105.04370	105.04370	3121
34 LAT	DEGREES	39.858	39.804	39.83064	39.83064	3121
35 TRK ANG	DEGREES	313.111	311.510	312.08458	312.08480	3121
36 HDG	RADIANS	5.496	5.410	5.45239	5.45241	3121
37 VE	M/SEC	-82.071	-85.818	-84.17617	84.18227	3121
38 VN	M/SEC	78.414	73.974	76.04477	76.05794	3121
39 ALTITUDE	KM	2.612	2.392	2.41049	2.41049	3121
40 TEMPC	DEGREES C	23.458	22.310	22.84278	22.84376	3121
41 EW WND SPD	KNOTS	9.351	-16.032	-7.78967	9.22385	3121
42 NS WND SPD	KNOTS	7.154	-17.897	-.60240	6.27648	3121
43 WIND SPEED	KNOTS	18.503	2.391	10.84520	11.15677	3121
44 WIND DIREC	DEGREES	359.998	.072	105.75741	129.53243	3121
45 AIRSPEED R	M/SEC	122.176	107.545	112.42393	112.45970	3121
46 AIRSPEED C	M/SEC	119.203	106.668	110.73093	110.76639	3121
47 AIRSPEED L	M/SEC	121.133	107.221	111.49930	111.53747	3121
48 DELTA ALT	METERS	195.070	-24.882	-6.41525	8.34518	3121
49 INRTL DISP	METERS	0.000	-15.034	-5.23568	6.53721	3121
50 UG RIGHT	M/SEC	5.250	-11.902	-.00000	3.73122	3121
51 UG CENTER	M/SEC	4.576	-10.520	-.00000	3.68761	3121
52 UG LEFT	M/SEC	4.812	-11.826	-.00000	3.75082	3121
53 VG RIGHT	M/SEC	4.611	-6.089	-.01278	1.71976	3121
54 VG CENTER	M/SEC	4.474	-6.336	-.01492	1.79824	3121
55 VG LEFT	M/SEC	4.239	-7.339	-.01482	1.76225	3121
56 WG RIGHT	M/SEC	7.622	-8.356	-.04249	2.22740	3121
57 WG CENTER	M/SEC	6.933	-6.061	-.03757	2.03396	3121
58 WG LEFT	M/SEC	8.091	-5.981	-.03986	2.09167	3121